

A FREQUENCY COMB FOR AN OPTICAL WDM NETWORK

The invention relates to the field of optical transmission systems and networks, and more particularly to those which implement wavelength division multiplexing (WDM) which can also be referred to as "multiplexing by optical frequency distribution".

A WDM signal comprises a combination of optical signals each constituted by an optical carrier wave modulated as a function of information to be transmitted. Each carrier wave possesses an optical frequency f_i (or wavelength) that is specific thereto and that enables a corresponding spectrum channel to be defined.

In order to rationalize the implementation of WDM optical systems so as to make it possible to use components (laser sources, filters, ...) produced by a variety of manufacturers, the optical frequencies used as carriers have been standardized. Thus, the International Telecommunications Union (ITU) has defined standard charts of regularly spaced apart carrier frequencies.

At present, depending on the chart under consideration, the pitch of the chart, i.e. the spacing df between the frequencies of two adjacent channels can be 50 gigahertz (GHz), 100 GHz, 200 GHz, or 400 GHz. Figure 1 shows such an optical frequency allocation chart with channels symbolized by vertical line segments arranged along a frequency axis f .

In order to make up an N-channel WDM, it is generally desirable to minimize the amount of spectrum occupied by the multiplex signals conveyed in the network. Under such circumstances, and as shown in Figure 1, N consecutive carrier frequencies $f_1, \dots, f_i, \dots, f_N$ are selected (symbolized by vertical arrows), from one of the standard charts (symbolized by vertical dashed line segments) at a pitch df which is large enough to provide sufficient spectral separation between channels, i.e. a pitch df that is not less than the amount of spectrum occupied by each channel (which

depends directly on the modulation frequency and on its format).

The transmission of optical signals in optical fibers and various other pieces of equipment in optical networks leads to losses that make it necessary in particular to introduce amplifiers for compensating such losses. However, in order to reduce the cost of networks, it is also desirable to limit the number of amplifiers that are installed, which means that it is necessary to maximize the output powers from said amplifiers. Unfortunately, increasing power comes up against a limit due to various non-linear phenomena which occur in fibers and certain components of networks. In particular, optical gates which are in widespread use in optical switches are based on semiconductor optical amplifiers which present behavior that is highly non-linear.

A non-linear phenomenon that is specific to signals that are multiplexed by optical frequency distribution is the phenomenon known as four-wave mixing (FWM). As is well known, this phenomenon can lead to cross-talk between channels when their frequencies are regularly spaced apart.

Thus, making up a multiplex in compliance with a chart that is standardized and optimized from the point of view of spectrum occupancy, as described above, can be incompatible with increasing power, if the resulting four-wave mixing leads to excessive signal degradation. In particular, the effects of this phenomenon are particularly penalizing when the spectral spacing between channels is small.

In order to avoid this phenomenon, limiting power levels or increasing spectrum gaps between channels would lead to increasing cost and/or under-using the passband of networks. For equal performance, if the output power from amplifiers is reduced, it becomes necessary to increase the number of amplifiers. Furthermore, given

the fact that the spectrum width of a WDM must always be limited in practice, at best by the passband of the links and in particular by that of the amplifiers, if the spectrum intervals are to be increased, then the number N
5 of channels must be decreased, and consequently the total data rate conveyed by the network is reduced.

This problem is raised in the article entitled "Reduction of four-wave mixing cross-talk in WDM systems using unequally spaced channels", by Fabrizio Forrghieri
10 et al., in IEEE Photonics Technology Letters, Vol. 6, No. 6, June 1994, pp. 754-756. That article shows that it is possible to find combs of N carrier frequencies that are irregularly distributed in a chart, such that all cross-talk by four-wave mixing is avoided and such
15 that the resulting increase in spectrum width is minimized. A first condition is that the spacing between the frequencies of any pair of channels should be different from the spacing between the frequencies of any other pair. Thereafter, of those combs which satisfy the
20 first condition, a comb should be selected in which the spectrum presents the smallest total width. Combs satisfying those two conditions can be found as solutions to a linear programming problem of conventional type.

Although that solution completely solves the problem
25 of four-wave mixing, it does not take account of problems associated with extracting channels from the multiplex, i.e. demultiplexing the WDM signal.

In principle, an extraction or "drop" operation consists in coupling the WDM signal to the input of a
30 filter set on the frequency of the channel that is to be dropped. To drop N channels at a time, it is possible to use N separate filters each coupled to the WDM signal. It is also possible to replace the filters by a demultiplexer designed to have N outputs set respectively
35 on the N frequencies of the multiplex. To be able to drop any one selected channel, it is also possible to use a 1 to N space-division switch whose outputs are coupled

respectively to the N inputs of a multiplexer, the N inputs being set respectively on the N frequencies of the multiplex.

Solutions based on multiplexers or demultiplexers
5 are preferable since they give rise to a smaller amount of loss than occurs in filters. However they constitute solutions that are economically acceptable only insofar as it is possible to use components that are commonly available on the market, such as arrayed waveguide
10 gratings (AWG) or "phasars". In general, the demultiplexers that are manufactured industrially are designed to select N frequencies f_1, \dots, f_N that are regularly spaced apart as in the standard charts as shown in Figure 1. With such a comb, a distribution of
15 frequency spacing values Δf is obtained as shown in Figure 2: the spacing Δf occurs $N-1$ times, the spacing $2\Delta f$ occurs $N-2$ times, etc.

In contrast, by adopting the solution set out in the above-specified article, uniform distribution of
20 frequency spacing values is obtained, but in order to drop channels, that requires special demultiplexers or demultiplexers of very large dimensions. Furthermore, the N frequencies extend over a greater width of spectrum.

25 An object of the invention is to remedy those drawbacks by proposing a multiplex structure of the optical carrier frequency comb type having the property of limiting the effects of four-wave mixing, while enabling channels to be dropped, in compliance with said
30 combs and by means of demultiplexers that are simple and inexpensive.

To this end, the invention proposes a compromise which consists in selecting from the frequencies of a standard type of chart those frequencies which are not
35 regularly spaced apart, but without attempting to solve the problem of four-wave mixing in full. However, the frequencies are selected in such a manner as to be able

to take advantage of the periodic property of the optical filter functions presented by ordinary demultiplexers and multiplexers.

More precisely, the invention provides a comb of
5 optical carrier wave frequencies allocated respectively
to N spectrum channels constituting an optical multiplex
signal, said comb frequencies being spectrally spaced
apart in irregular manner while all belonging to an
optical frequency allocation chart that is spectrally
10 spaced apart in regular manner at a pitch df , the comb
being characterized in that said comb frequencies are
selected in such a manner as to enable them to be dropped
from said multiplex signal by N respective periodic
optical filtering operations having the same free
15 spectrum interval equal to $M \cdot df$, where M is an integer
equal to or greater than N, said filtering operations
enabling N consecutive frequencies of the chart to be
dropped, and in that the spacing between any pair of
frequencies of said comb is different from any integer
20 multiple greater than or equal to 1 of said free spectrum
interval.

By selecting N carrier frequencies satisfying those
criteria for constituting a multiplex, channel extraction
can be performed by means of a single conventional
25 regular demultiplexer having one input and N outputs,
such as an array waveguide demultiplexer.

A demultiplexer of this type has the property
whereby its transmittance relative to the input for each
of its N outputs presents a common free spectrum
30 interval. It is therefore equivalent to N periodic
optical filters each presenting the same free spectral
interval. To extract the N frequencies in accordance
with the invention, a demultiplexer is thus selected that
has N outputs set on N consecutive frequencies of the
chart and presenting the free spectrum interval df of the
35 invention, i.e. equal to $M \cdot df$ where M is an integer
multiple that is necessarily greater than or equal to N.

This condition ensures that the demultiplexer can spatially separate N consecutive frequencies of the chart. Since the N carrier frequencies of the invention are also such that the spacing between any two of them is
5 different from any integer multiple greater than or equal to 1 of the free spectrum interval Δf , the demultiplexer can also spatially separate these N carrier frequencies.

Advantageously, the values of the spacings between pairs of frequencies of the comb are not all distinct.
10 Thus, the irregular spacing of the channel frequencies on the chart leads to limiting the consequences of four-wave mixing, but the fact of accepting spacing between the frequencies of certain pairs of channels that are equal to the spacing between the frequencies of other pairs of
15 channels means that full immunity to said phenomenon is not guaranteed. However, it does make it possible to find more combs that satisfy the criteria of the invention, and in particular combs of spectrum width that is smaller than is the case for combs made up of the same
20 number of channels and that are completely insensitive to four-wave mixing.

Nevertheless, in practice, it is appropriate to seek an optimum compromise between spectrum width and the degree of insensitivity to four-wave mixing. To do this,
25 it is possible to evaluate the magnitude of the effects of four-wave mixing as a function of the distribution of spacing values between the frequencies of combs satisfying the above criteria by simulating of transmission through conventional non-linear media. By
30 setting a limit for these effects, it is possible to deduce an additional condition for imposing on the frequencies of the comb.

Thus, according to another advantageous characteristic of the invention, it has been found that
35 the frequencies of the comb should preferably be selected in such a manner that the spacings between pairs of said

frequencies do not take on the same value more than $5N/9$ times.

According to another characteristic of the invention, $M = N$. This condition has the effect of making it possible to find combs having a spectrum width that is minimized for given values of df and of N . This also implies that the above-mentioned demultiplexer adapted for extracting the channels is a cyclical demultiplexer. Since demultiplexers of this type are also commonplace components, this condition does not have any undesirable consequences concerning the cost of dropping channels.

The invention also provides an optical multiplex signal made up of N spectral channels having allocated thereto N respective optical carrier wave frequencies belonging to a comb as defined above.

The invention also provides an optical transmission array using optical frequency distribution multiplexing for conveying at least one optical multiplex signal made up of N spectral channels to which there are allocated N respective optical carrier wave frequencies belonging to a comb as defined above.

Advantageously, in such an array, provision is made for a plurality of multiplex signals to be associated with a respective plurality of mutually different combs. This disposition is advantageous for limiting problems of cross-talk between channels in optical routers where frequency selectors receive a plurality of multiplex signals.

Other aspects and advantages of the invention appear in the following description given with reference to the figures.

- Figure 1 shows an optical frequency chart and is described above.

- Figure 2 shows the distribution of frequency spacing values for a conventional optical frequency comb.

- Figure 3 shows an example of an optical frequency comb of the invention.

- Figure 4 shows an optical router element for a WDM network in accordance with the invention.

5 Figure 3 shows an example of an optical frequency comb in accordance with the invention for the particular case where $N = 4$.

10 The optical frequency chart has a pitch df and comprises frequencies $f_1, f_2, \dots, f_{13}, \dots$ represented by vertical line segments disposed along a frequency axis f . To make up the comb, the four frequencies selected are f_2, f_5, f_7 , and f_{12} as symbolized by vertical arrows.

15 The comb is devised so as to define a free spectrum interval Df equal to $4df$, while satisfying the condition that the spacing between any pair of frequencies of the comb is different from any integer multiple greater than or equal to 1 of the free spectrum interval $4df$.

20 In this example, the frequencies of the comb are selected in such a manner as to enable them to be dropped from a multiplex signal by means of a cyclical demultiplexer having four outputs set on four consecutive frequencies of the chart and presenting the free spectrum interval $4df$.

25 For other values of N , it is still possible to find frequency values and a free spectrum interval Df that can satisfy the conditions of the invention. To make it easy to find such values, it is possible to use conventional linear programming methods.

30 Figure 4 shows how multiplex combs of the invention can be used in an optical transmission network that makes use of optical frequency distribution multiplexing and that is adapted to such combs.

35 The apparatus shown serves to drop selectively any one of the channels $S(f_i)$ belonging to any one two received multiplex signals WDM_1, WDM_2 .

 In this example, each multiplex signal has four spectrum channels which are allocated to four respective

optical carrier wave frequencies belonging to a comb of the invention. Thus, the comb of the multiplex WDM1 is made up of the frequencies f_2 , f_5 , f_7 , and f_{12} , while the comb of the multiplex WDM2 is made up of the frequencies f_1 , f_4 , f_6 , and f_{11} .

The apparatus includes a periodic multiplexer MUX such as an AWM and it is provided with four inputs P1 to P4 set respectively on the four frequencies f_1 , f_2 , f_3 , and f_4 , with a free spectrum interval D_f selected to be equal to $4df$. This is thus a cyclical periodic multiplexer whose four inputs are set respectively on the four frequencies f_1 , f_2 , f_3 , and f_4 , modulo $4df$.

Each of the four inputs is disposed so as to receive a fraction of each of the multiplex signals WDM1 and WDM2 via optical gates G1-G8. Thus, to drop any one of the channels $S(f_i)$ belonging to either one of the two multiplex signals WDM1 and WDM2, it suffices to activate one of the optical gates. In this example, the gates G1 to G8 make it possible to drop the frequencies f_5 , f_1 , f_2 , f_6 , f_7 , f_{11} , f_{12} , and f_4 , respectively.

It should be observed that a single periodic multiplexer can be used to drop the multiplexes associated with different combs of the invention. With apparatus of the type shown in Figure 4, in particular, the fact of selecting different combs presents the advantage of reducing the risks of cross-talk at the inputs of the multiplexer due to imperfect isolation of the optical gates.

The frequency selector apparatus of Figure 4 can easily be generalized for combs of the invention comprising an arbitrary number N of frequencies, and for an arbitrary number of input multiplex signals.

This apparatus can constitute a basic element for making up an optical router or a WDM photonic switching matrix. To do this, it suffices to provide a plurality of said apparatuses for each output of the matrix and to

couple their outputs to the associated output of the matrix.